

AD-A152 195

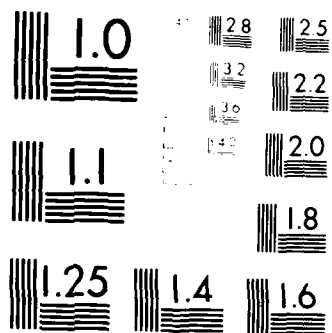
A SHORT RANGE HIGH ACCURACY RADAR RANGING SYSTEM(U) AIR 1/1  
FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF  
ENGINEERING K E THOMSEN DEC 84 AFIT/GE/ENG/84D-66

UNCLASSIFIED

F/G 17/9

NL

										END			



MICROCOPY RESOLUTION TEST CHART  
 NATIONAL BUREAU OF STANDARDS-1963-A

DTIC  
①

AD-A152 195



A SHORT RANGE, HIGH ACCURACY

RADAR RANGING SYSTEM

THESIS

Kurt E. Thomsen  
Captain, USAF

AFIT/GE/ENG/84D-66

This document has been approved  
for public release and sale; its  
distribution is unlimited.

DTIC  
ELECTE  
S APR 02 1985 D  
E

DTIC FILE COPY

DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY

**AIR FORCE INSTITUTE OF TECHNOLOGY**

Wright-Patterson Air Force Base, Ohio

85 03 13 055

AFIT/GE/ENG/84D

A SHORT RANGE, HIGH ACCURACY

RADAR RANGING SYSTEM

THESIS

Kurt E. Thomsen  
Captain, USAF

AFIT/GE/ENG/84D-66

Approved for public release; distribution unlimited

A SHORT RANGE, HIGH ACCURACY  
RADAR RANGING SYSTEM

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Electrical Engineering



X

Kurt E. Thomsen, B.S.  
Captain, USAF

December 1984

A-1

Approved for public release; distribution unlimited

## Preface

The purpose of this study was to determine the feasibility of measuring the separation between two aircraft in flight with a high degree of accuracy. This information is utilized in the testing of the flight characteristics of aircraft that are in rain or icing conditions.

I selected this topic because it presented me with a unique opportunity: the chance to take a project from the concept stage all the way through the design, construction and hardware testing. While there were times when I questioned my sanity for attempting this effort in the end I found the experience to be extremely rewarding.

Throughout the course of this thesis I received a great deal of help from others. I would like to thank my faculty advisor, Major Ken Castor, for the advice and guidance that he provided me with. I also wish to thank two friends from the Aeronautical Systems Division: Dr. Dave Krile for his countless tips on the hardware design, and Gary Kretzler for the many hours he spent helping me test the system. And finally, a special thanks to my wife Debi for her help in drawing all of the figures and for putting up with me when all was not going well.

Kurt E. Thomsen

## Table of Contents

	Page
Preface.....	ii
List of Figures.....	v
List of Abbreviations.....	vii
Abstract.....	ix
I. Introduction.....	1
II. Problem Statement.....	4
Statement of Objectives.....	4
Description of Operational Scenario.....	5
Description and Analysis of Possible Solutions.....	7
Navstar Global Positioning System.....	8
Laser Radar.....	9
Pulsed Radar.....	10
Frequency Modulated Continuous Wave Radar.....	11
III. Theory of Operation.....	13
Explanation of FM-CW Radar.....	13
Description of a Typical FM-CW System.....	19
IV. Description of Design.....	22
Description of a Typical Tracking System....	23
First Tracking Circuit Design.....	25
Final Tracking Circuit Design.....	31
Complete Ranging System Design.....	42
V. Test Results.....	46
Tracking Circuit Tests.....	46
Complete Ranging System Tests.....	51

VI.	Conclusions and Recommendations.....	60
	Conclusions.....	60
	Recommendations.....	62
	Bibliography.....	64
	Vita.....	65



## List of Figures

Figure	Page
1. Typical Aircraft Position During Icing Mission.....	6
2. Frequency vs. Time Relationship for Various Modulating Waveforms.....	15
3. Difference Frequency vs. Time Relationship for Various Modulating Waveforms.....	16
4. Effect of Doppler on Difference Frequency.....	18
5. FM-CW Range Measuring System.....	20
6. Typical Tracking System.....	23
7. Initial Frequency Tracking Circuit.....	26
8. Final Frequency Tracking Circuit.....	31
9. Half-lattice Crystal Filter.....	33
10. Tracking Circuit Schematic.....	36
11. Ranging System Components.....	42
12. Upper and Lower Filter Frequency Response.....	47

13. Sum and Difference Volts vs. Frequency.....	49
14. VCO Output Frequency vs. Input Frequency.....	50
15. System Range vs. Frequency Response.....	56
16. Range Resolution Test Results.....	58

### List of Abbreviations

AGC	automatic gain control
bps	bits per second
BW	bandwidth
CW	continuous wave
dB	decibel
dBm	decibels above one milliwatt
DC	direct current
DIP	dual inline package
$f_d$	difference frequency
$f_{dop}$	doppler frequency
$F_{cal}$	calculated frequency
F-center	overlap frequency of two filters
$F_o$	filter center frequency
FM-CW	frequency-modulated continuous wave
GHz	gigahertz
GPS	Global Positioning System

HP	Hewlett-Packard
Hz	hertz
IF	intermediate frequency
KHz	kilohertz
L	length
LED	light emitting diode
LO	local oscillator
Mbps	megabits per second
MHz	megahertz
PRN	pseudorandom noise
Q	quality factor
RF	radio frequency
TWT	travelling wave tube
VCO	voltage controlled oscillator
Vr	radial velocity
$\Delta F$	difference between measured and calculated frequencies
$\lambda$	wavelength

### Abstract

This paper describes the design and test of a low power, highly accurate FM-CW radar ranging system. The objective of the design was to provide an inexpensive aircraft-to-aircraft ranging system with  $\pm 1$  foot accuracy at ranges up to 400 feet.

Particular detail is given to describing the design and test of the frequency tracking circuit. Quartz crystals were used to make the narrow bandpass filters necessary for good frequency resolution. The design of the rest of the system was kept simple by using standard electronic test equipment.

The system was tested for its range accuracy and range resolution capabilities. The results show that the system was limited by ground clutter and the performance of the test equipment available. However, given the right equipment in an airborne environment the accuracy desired for the system is possible.

# **A SHORT RANGE, HIGH ACCURACY RADAR RANGING SYSTEM**

## **Chapter 1**

### **INTRODUCTION**

Flight testing of aircraft has historically concentrated on determining the performance of an aircraft when it was flown in clear air. At Edwards Air Force Base in California testing is currently under way to determine the flight characteristics of aircraft under adverse weather conditions. Rain or icing conditions can be simulated in tests conducted at high altitudes. In these tests a specially modified tanker aircraft discharges a spray of water. The test aircraft flies through the spray allowing data to be gathered concerning its performance while in rain or when ice has built up on the surface of the aircraft. To do the tests properly the separation distance between the tanker and the test aircraft in flight must be known. The purpose of this study was to determine the feasibility of measuring the range between two aircraft to a high level of

accuracy. This report was written in response to a request made by the 6520th Test Group, Edwards AFB, CA, who sponsored this effort.

Chapter 2 begins by defining the specific goals of this study and by also explaining what will not be done. A detailed description of the operational scenario of the flight tests will be given. Four possible methods of solving the ranging problem (Navstar Global Positioning System, laser radar, pulsed radar, and frequency modulated continuous wave (FM-CW) radar) are considered. A brief description of the theory behind each system is given, along with the advantages and disadvantages of using each one to perform this ranging task. Based on this information an FM-CW approach is selected for further study.

In Chapter 3 the theory of FM-CW radar is explained, followed by an outline of a typical system. Chapter 4 describes the design process that leads to the final ranging system. It begins by explaining the need to design a frequency tracking circuit and goes on to specify how a generic tracking system works. An initial tracking circuit that was built but did not work is analyzed, followed by a detailed description of a second tracking circuit that was used in the final design. Chapter 4 concludes by listing the remaining components that make up the ranging system.

Chapter 5 describes the tests used to analyze the performance of the system. Tests performed on the tracking circuit are examined first, followed by an explanation of how the tracking circuit performance will affect the operation of the entire ranging system. Tests are then run on the complete system and the data gathered is analyzed and compared with the goals listed in Chapter 2. In Chapter 6 the results that were obtained are explained and recommendations are made concerning future work in this area.



## Chapter 2

### PROBLEM STATEMENT

In Chapter 1 a brief description of the problem was given. In this chapter a specific statement of the problem is presented, as well as a description of a typical operational scenario. Several different system designs are examined and the advantages and disadvantages of each are discussed. Finally, one system was chosen for further study, fabrication, and testing.

#### 2.1 Statement of Objectives

This thesis resulted from a request made by the sponsoring organization for an inexpensive way to measure the distance between two aircraft. Their requirements for the system were

target range between 25 and 400 feet

accurate to within  $\pm 1$  foot

a real-time display of target range on both aircraft

the ability to record the range for later analysis

telemetry capability

ease of mounting/dismounting from the aircraft.

It is important to point out that the primary objective of this thesis was not to deliver fully certified flight test hardware, but only to demonstrate the feasibility of accomplishing the task. With this in mind, only the technical aspects of the requirements were emphasized -- the requirements that were not technological challenges (real-time display, data recording/telemetry capability, mounting considerations) were not considered specific goals of this effort.

## 2.2 Description of Operational Scenario

To fully appreciate some of the problems discussed in later chapters, it is first necessary to understand the operational



Figure 1. Typical aircraft position during icing mission.

scenario that brought about the requirements. Two aircraft fly at approximately 30,000 feet, one directly behind the other. The lead aircraft (a KC-135 tanker) is about 25 feet above and 25 to 400 feet in front of the other. The trailing aircraft (which may be of any type) flies a path that is parallel to that of the tanker, but it may be displaced laterally to allow any portion of it to be in the same vertical plane as the centerline of the tanker. The relative velocity between the two aircraft is nominally zero knots, and will not exceed four knots. The two aircraft may fly

over any type of terrain (mountainous, desert, water, etc.), and there are no other aircraft in the vicinity. Figure 1 shows how two aircraft with minimum horizontal separation (approximately 25 feet) would appear.

### 2.3 Description and Analysis of Possible Solutions

Prior to starting on the hardware design for this system it was necessary to select a suitable ranging method. The ranging problem has been around for many years, and there are many different ways to determine the range to a target. The approaches that were considered were

Navstar Global Positioning System

laser radar

pulsed radar

frequency modulated continuous wave radar.

Certainly, these methods do not represent every possible way of solving the ranging problem. It was felt, however, that these methods would provide a reasonable number of different approaches to solving the problem.

### 2.3.1 Navstar Global Positioning System

The Navstar Global Positioning System (GPS) is currently being developed by the military as a means of providing accurate time and position information to users. When the system is fully operational in 1988 it will consist of 18 Navstar satellites (plus 6 spares) in 11,000 mile earth orbits. A user (man or machine) with a GPS receiver will be in sight of at least four satellites at any time. The satellites work by transmitting two pseudo-random noise spread spectrum signals at 1,575 and 1,227 MHz. Timing and navigation data is modulated at a rate of 50 bps on a P-code or PRN sequence of digits impressed onto each carrier at 10.23 Mbps. By decoding the signals from the satellites a GPS receiver can determine its position to an accuracy of 15 meters [1:68].

The advantage of using a GPS-based ranging system is that the development work on the Navstar system has already been done. Thus only a minimal amount of hardware design and integration would be required to complete the ranging device. The disadvantage of this approach is that the 15 meter accuracy of the Navstar system is not good enough for this application. Also, since the system has not been fully deployed the satellites and receivers required may not be readily available.

### 2.3.2 Laser Radar

Any radar whose transmitted energy is light generated by a laser is called a laser radar. Laser radars may be of any type and can perform the same functions as any other type of radar (pulsed or continuous wave (CW), coherent or noncoherent, etc.). The use of an optical carrier frequency enables laser radars to take advantage of the benefits inherent in higher frequencies: higher bandwidths allow shorter pulses and better range resolution, while the narrower beams (for a given antenna size) result in greater angular resolution. An example of a high performance laser radar is a system developed by NASA for spacecraft rendezvous and docking. In its short range mode (range between zero and three kilometers) this system achieved a range accuracy of  $\pm .1$  meter and an angular accuracy of  $\pm .1$  degree [2:130]. This level of performance would have been more than adequate for this effort; however, the disadvantages of laser radars ruled out their implementation in this case. Laser energy attenuates more rapidly in all atmospheric conditions than does microwave energy. Operating a laser radar in the vicinity of a water spray might yield results that are inaccurate or incorrect. Also, directing a laser beam at an aircraft cockpit from a range of 25 feet would pose a serious safety problem.

### 2.3.3 Pulsed Radar

Pulsed radar is the most common approach to measuring the range to a target. Range is determined by finding the amount of time needed for a pulse of radio frequency (RF) energy to travel to the target and be reflected back to the receiver. The characteristics of the transmitted pulse determine the performance limits of the system. The range accuracy of the radar is a function of the rise time of the pulse: good range accuracy calls for a pulse with a sharp leading edge. Range resolution requires that a short pulse be transmitted, or that a long pulse be converted into a short pulse by pulse compression. To have a short minimum range it is critical that the radar receiver be well isolated from the transmitter.

To meet the objectives listed at the beginning of this chapter, a pulsed radar would have to satisfy some stringent requirements. Accuracy of one foot means that the bandwidth must be at least one gigahertz. Also, the timing jitter (the uncertainty of when the transmitter fired) must be considerably less than one nanosecond. Range resolution of one foot (needed to ensure that only a single point on the target aircraft is tracked) can be achieved by a pulse with an effective width no greater than two nanoseconds. The

short minimum range rules out using a single transmit/receive antenna. Two antennas would be needed for adequate receiver protection.

#### 2.3.4 Frequency-Modulated Continuous Wave Radar

Frequency-modulated continuous wave radars have been in use since the 1920s, and today are most often utilized as aircraft radar altimeters. In an FM-CW radar the frequency of the transmitted signal is changed as a function of time in a known manner. Triangular, sawtooth, sinusoidal, or other waveforms can be used to modulate the carrier frequency. Range to a target is determined by comparing the received signal to a sample of what is being transmitted: the target range is proportional to the difference in frequency between these two signals. Range accuracy is a function of the frequency deviation rate: good range accuracy requires a rapidly changing transmit frequency. Range resolution is determined by the bandwidth of the filters used in the frequency tracking circuitry.

Performing this task with an FM-CW radar would require a wide bandwidth, just as a pulsed radar would. The big advantage to using an FM-CW system is that the range information is conveyed in the frequency domain and not in the time domain. It is easier to measure small differences



in frequency than it is to measure small differences in time. Wide bandwidth sweep oscillators and high accuracy frequency counters are readily available; nanosecond timing errors would not be important in an FM-CW system. While the other systems described could probably have been made to work, it was decided that the most practical approach to solving this problem was to use an FM-CW radar.

## Chapter 3

### THEORY OF OPERATION

In Chapter 2 descriptions of some possible system solutions were given, leading to a decision to use an FM-CW radar design approach. This chapter will explain the theory of operation of an FM-CW system, and describe a typical FM-CW system design.

#### 3.1 Explanation of FM-CW Radar

Unlike pulsed radar systems where the RF carrier is keyed on and off (amplitude shift keying), FM-CW radars transmit a carrier signal whose amplitude is constant, but whose frequency is made to vary as a function of time. A mathematical example of this might look like

$$S(t) = A \cos(2\pi f_0 t + G(t)) \quad (1)$$

where

$S(t)$  is the transmitted signal

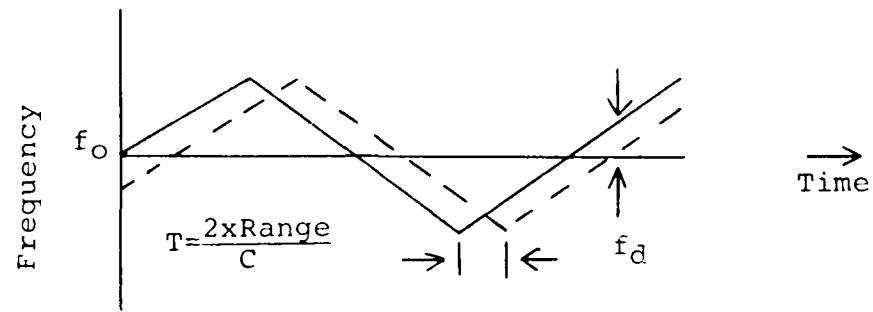
$A$  is the signal amplitude

$f_0$  is the carrier frequency

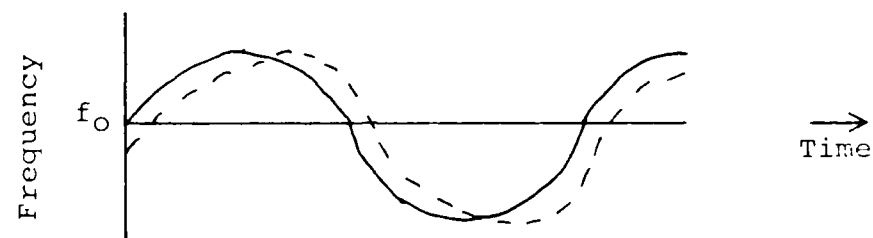
$G(t)$  is the modulating waveform.

Figure 2 illustrates what the transmitted frequency looks like for various functions  $G(t)$ . The solid line represents the signal that was transmitted, while the dashed line represents the signal returned from a point target. Since the frequency of the transmitted signal is constantly changing there will be a frequency difference ( $f_d$ ) between the transmitted and received signals. The magnitude of this difference is a function of the range to the target, as well as how fast the transmit frequency is swept. This is plotted versus time in Figure 3.

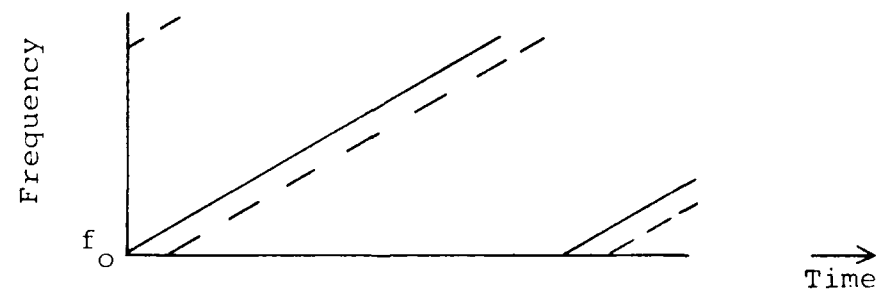
FM-CW radars determine the range to a target by measuring the difference frequency. When triangular modulation is used the difference is nearly constant, except for the moments when the transmit frequency begins to sweep the other direction. By making the ratio of the period of the modulating signal to the maximum time required for the energy



(a)

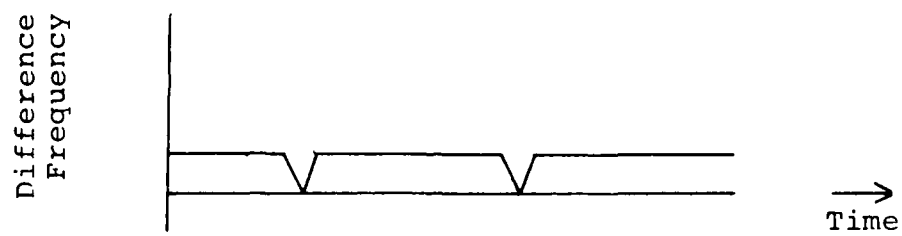


(b)

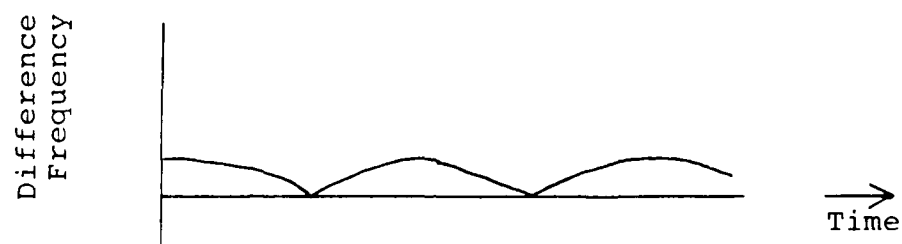


(c)

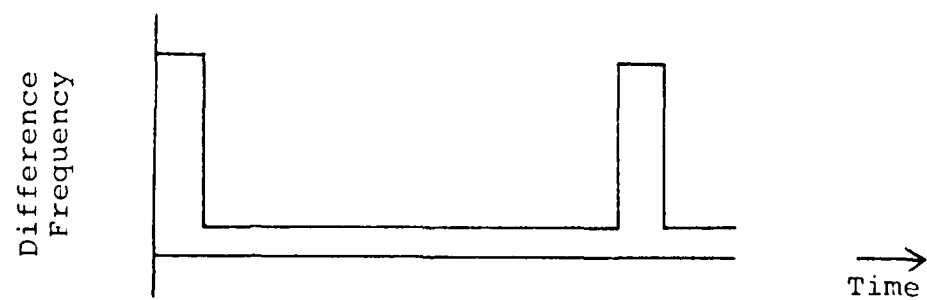
Figure 2. Frequency vs. time relationship for various modulating waveforms. (a)--Triangular (b)--Sinusoidal (c)--Ramp



(a)



(b)

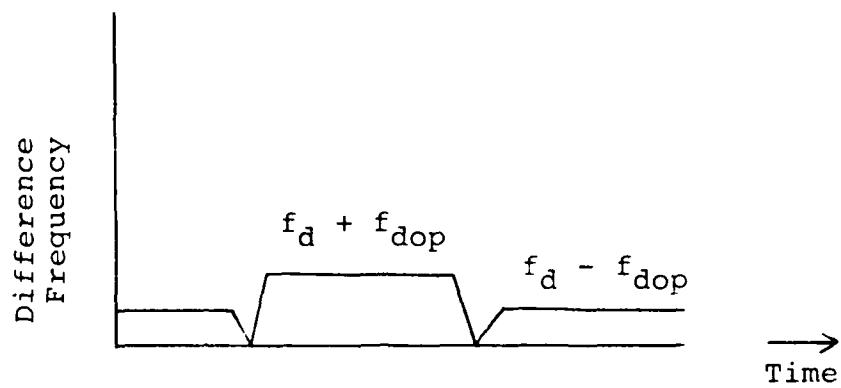


(c)

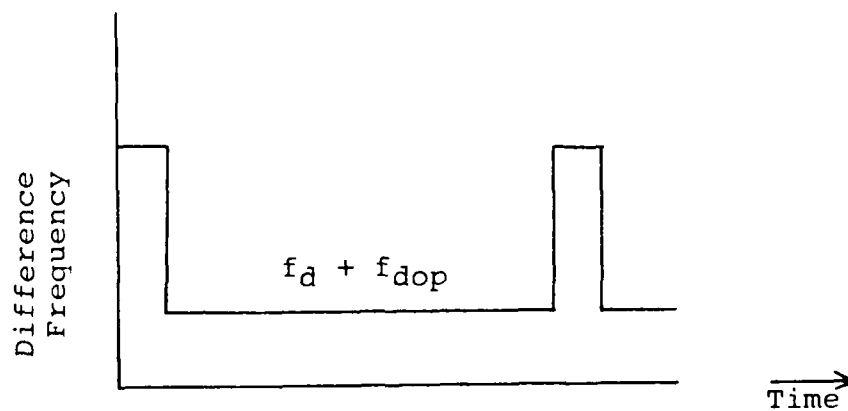
Figure 3. Difference frequency vs. time relationship for various modulating waveforms. (a)--Triangular (b)--Sinusoidal (c)--Ramp

to reach the target and return large, the difference becomes essentially constant. For sinusoidal modulation the curve shown in Figure 3(b) is somewhat misleading: the difference frequency spectrum is not continuous, but actually consists of a number of discrete spectral lines. These lines are bracketed around the modulating frequency and its harmonics, and their amplitudes are a function of the target range [3:16-22,16-23]. While obtaining target range information from these spectral lines is possible, it is much more difficult than from a constant difference frequency.

The difference frequency for a ramp modulating signal, shown in Figure 3(c), is also constant except for times near the flyback of the ramp. Just as with triangular modulation, this effect can be ignored if the frequency of the modulation is low enough, making a ramp waveform good for measuring target range. The main drawback to this type of modulation, however, is its susceptibility to error caused by relative target motion. If the range to the target is changing, the frequency of the return signal will contain a doppler shift ( $f_{dop}$ ). Figure 4 shows the results of a positive doppler shift (approaching target) on the difference frequencies generated by triangular and ramp modulating signals. By using triangular modulation the doppler shift can be averaged out, yielding an indication of the true target range. With a ramp modulating signal relative target motion produces a



(a)



(b)

Figure 4. Effect of doppler on difference frequency.

(a)--Triangular modulation (b)--Ramp modulation

constant change in the difference frequency. Since this bias cannot be removed, ramp modulation is limited to situations where no target motion is expected.

### 3.2 Description of a Typical FM-CW System

The high level of accuracy required for this system presents the main challenge to the design. An aircraft is a complex radar target composed of a large number of discrete radar scatterers. As the aircraft flies its motion causes the radar cross section of each of the many scatterers to fluctuate. If the radar cannot discriminate between the multiple scatterers it will measure the distance to the centroid of the target. Radar cross section fluctuations will change the apparent position of the centroid, resulting in range error. To prevent this, the system must have good range resolution, and it must be able to track the first large scatterer on the target. Figure 5 briefly illustrates how an FM-CW radar system would be configured to measure target range.

The idea behind the operation of this system is simple. The sweep oscillator generates an RF carrier, frequency modulated by a triangular signal. A microwave coupler



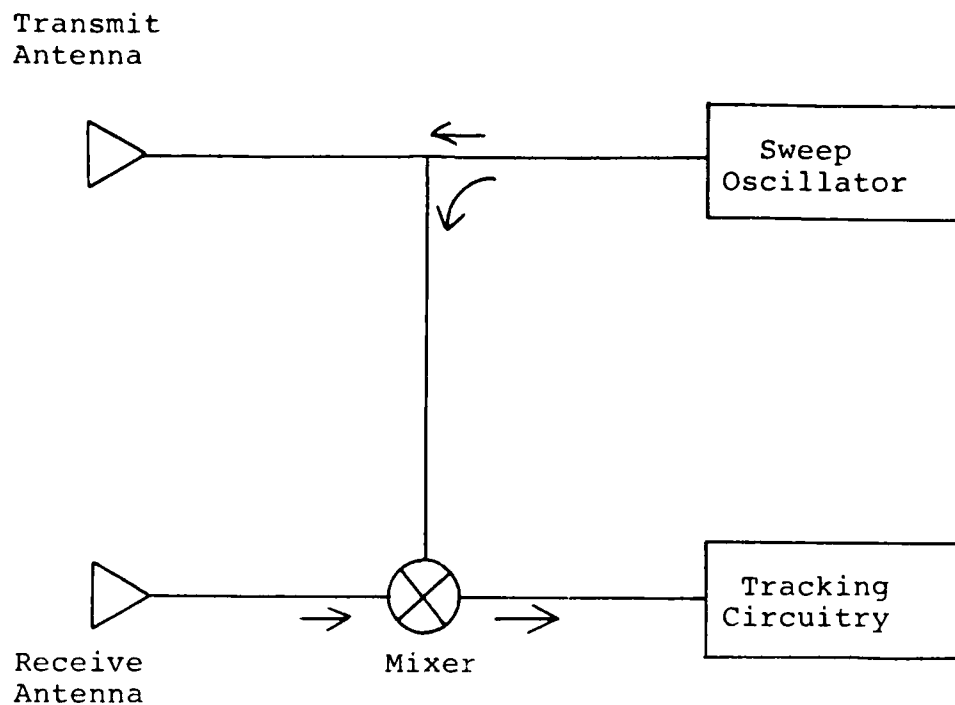


Figure 5. FM-CW range measuring system.

delivers a small fraction of the oscillator output power to a balanced mixer, while the rest would be transmitted. Some of the transmitted energy reflects from the target and is picked up by the receive antenna. This received energy forms the other mixer input, while the mixer output is the difference frequency between the transmitted and received signals. This output is fed to the frequency tracking circuit, which discriminates between closely spaced targets and tracks the nearest one. The range to the target is proportional to the frequency being tracked.

This system will be able to meet the performance objectives listed in Chapter 2 only if the following conditions are met. The sweep oscillator must be able to sweep over a wide frequency range, and do it in a short time (a large Hz/second ratio). This will insure that two targets that are closely spaced in range will be widely separated in frequency. Since there is a limit to how fast an oscillator can be swept, the frequency tracking circuit must be designed so that it can differentiate two targets that are very closely spaced in frequency. Thus, the overall performance of the system will be determined by the performance of the sweep oscillator and the frequency tracking circuit.

## Chapter 4

### DESCRIPTION OF DESIGN

The previous chapter contained a brief description of how an FM-CW radar system would be configured to solve a ranging problem. The key to this type of system is the frequency tracking circuit: if the frequency tracker does not perform well, then the entire system will not perform well. This chapter will look at the design of the ranging system in detail. First, a brief explanation will be given of a generic tracking system. A tracking circuit that did not work will be described, including the reasons why it was chosen and the reasons why it was discarded. The lessons learned from this failed attempt led to the frequency tracker that went into the final design, which is explained in the greater detail. Finally, the remaining components of the ranging system are examined.

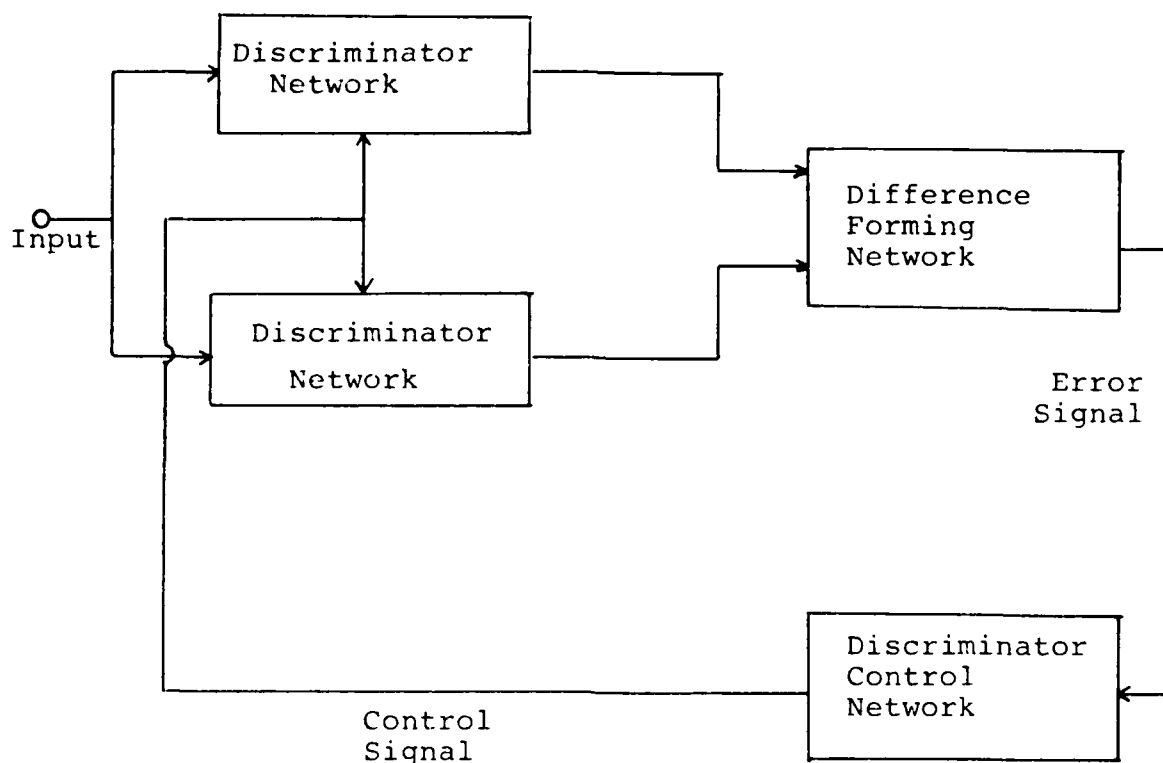


Figure 6. Typical tracking system.

#### 4.1 Description of a Typical Tracking System

In radar systems the output of the tracking circuitry is often an indication of some parameter: target range, azimuth angle (or bearing), elevation angle, or doppler. Tracking systems are used to give a continuous measure of one of these parameters. As was explained earlier, in an FM-CW radar the instantaneous difference between the transmitted and received

frequencies is proportional to the target range. Therefore, to track a target in range (using an FM-CW radar system) it is necessary to have a circuit that will track this instantaneous frequency difference.

Before getting into the specifics of a frequency tracking system it is useful to see how a general tracking system functions. Figure 6 shows how a typical tracking system might be constructed to track some parameter (angle, range, doppler, etc.) of a target. The input signal is applied to two discriminator networks, whose outputs are a function of the parameter being tracked. The discriminator networks are offset from each other so that the maximum output of each network occurs at a different value of the parameter being tracked. The output from each discriminator is applied to a difference network. Here, the discriminator outputs are subtracted from each other to produce a tracking error signal. The sign of the error signal (positive or negative) tells which discriminator network has a larger output, while the magnitude of the error signal tells how much larger it is. If the error signal is zero the output of the two discriminators are equal, and the tracking system is said to be "locked on."

The error signal is passed to a discriminator control network where a discriminator control signal is developed. When the control signal is applied to the discriminators the maximum output point of the two discriminators "move." "Move"

can mean different things, depending on what parameter is being tracked. If angle tracking is being done, "move" might mean that the antennas physically move. If range tracking is being done with a pulsed radar system, "move" could mean that the relative timing between two pulses change. For a system that tracks in frequency, "move" might mean that the center frequency of a filter bank has changed. In any case, the discriminators maintain their offset relative to each other. The control signal moves the discriminators in a manner that drives the error signal toward zero until lock on is achieved.

#### 4.2 First Tracking Circuit Design

In a frequency tracking circuit bandpass filters can be used as discriminator networks. The center frequencies of the two filters are offset so that the upper 3dB frequency of the low filter is the same as the lower 3dB frequency of the high filter. This frequency is called F-center. Moving the discriminator networks can be accomplished two different ways: either by fixing the input frequency and sliding the two bandpass filter center frequencies up or down, or by fixing the two filter center frequencies and sliding the input frequency up or down. The former method was selected

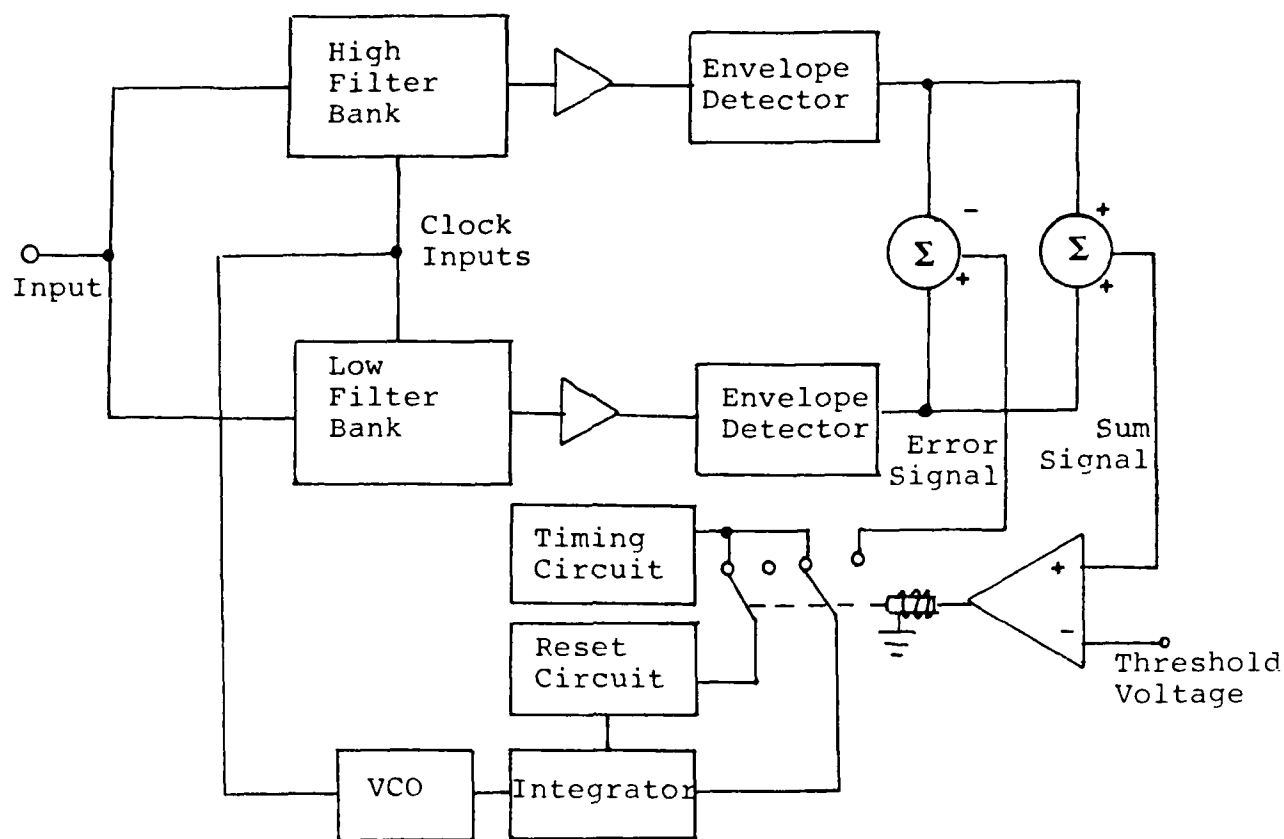


Figure 7. Initial frequency tracking circuit.

for the first tracking circuit design. A circuit designed to do this is shown in Figure 7. The reason that this approach was attempted first is because it offered the simplest design. The main challenge in a frequency tracking circuit is the design and construction of the bandpass filters: to get good tracking circuit performance the bandpass filters must have narrow bandwidths, and their center frequencies must be offset exactly. For the first tracking circuit attempt, the solution to this problem was to use switched capacitor filters. Switched capacitor filters work by sampling the input signal at a periodic rate to produce the

desired filter response. They were used because their center frequencies are proportional to an input clock frequency, and therefore by changing the clock frequency the filters can be tuned. Switched capacitor filters are available in integrated circuit form.

The upper and lower filters were constructed using National Semiconductor MF 10 integrated circuits. The MF 10 contains two second-order switched capacitor filters on a single 20 pin chip. Five chips were available, so by cascading sections two tenth-order bandpass filters could be realized. To get a narrow bandpass filter response, the quality factor (or Q) of the filter must be high. For a bandpass filter the quality factor is defined as

$$Q = F_o / BW \quad (2)$$

where  $F_o$  is the center frequency of the filter and BW is the 3dB bandwidth of the filter. When using an MF 10 the Q of the filter is determined by the ratio of resistors connected to the chip.

The performance of the filters was limited by the fact that, in an MF 10, the product of  $F_o$  and Q cannot exceed 200 KHz [4:4-21]. This presented a problem: what should the sweep rate of the oscillator be? If the frequency of the sweep oscillator is changed rapidly, two targets that are close in space will be widely separated in frequency. High sweep



rates allow wider filters to be used in the tracking circuit, and they also dictate that the filter center frequencies needed to track a target at maximum range must be higher. Since there appeared to be no clear advantage to either approach (high sweep rate, high  $F_o$ , low  $Q$  vs. low sweep rate, low  $F_o$ , high  $Q$ ) it was decided to use a maximum  $F_o$  of 5 KHz (for a target range of 500 feet). Since electromagnetic energy propagates approximately one foot per nanosecond in free space, a 5 KHz difference frequency for a target 500 feet from the radar (two way range equal to 1000 feet) dictates an oscillator sweep rate of five Hz per nanosecond.

Using this sweep rate, two targets spaced one foot apart will produce difference frequencies separated by 10 Hz. Hence, in order to get one foot resolution, the filter bandwidths must be 10 Hz. The filter sections were built and cascaded, and the upper and lower filter centers were offset from each other by 10 Hz. The smallest bandwidth that could be achieved for each filter bank was 20 Hz (at a center frequency of 5 KHz). Even though no better than two foot resolution could be hoped for (at 500 feet) with these filters, it was decided to continue with the switched capacitor filter design approach.

After the filters had been built the rest of the tracking circuit construction proceeded smoothly. The two filter outputs were each passed through non-inverting amplifiers (to provide buffering and gain balancing), and then envelope

detected. These signals were then summed, and the result was compared against a threshold voltage to make a target present/no target decision. The difference between the two envelope detected filter outputs was formed and, if a target was present, passed through an analog switch to an integrator. The integrator output would be connected to the control input of a voltage controlled oscillator (VCO). The VCO output was buffered and applied to the clock inputs of the two filter banks. If the target return frequency went above F-center the difference signal would become negative. Because a negative integrator was used, the integrator output would then go up, which caused the VCO output frequency to increase. This would cause F-center to increase until it equaled the target return frequency. If the return frequency went below F-center the difference signal would become positive, causing the VCO frequency to decrease until lock on was achieved. If a no target decision was made, a negative voltage was applied to the integrator. The integrator responded to this input by generating a positive ramp voltage. When this ramp was applied to the VCO it caused F-center to sweep upward. When the target return came within the capture range of the tracking circuit a target present decision would be made. The integrator would be disconnected from the negative voltage and connected to the difference signal, and the circuit would lock on to the target.

To determine the target range, the voltage on the control

input of the VCO could be measured. Another technique would be to measure the output frequency of the VCO. Either signal is proportional to the target range, but counting the VCO frequency would yield better results. By using a gating period on the counter that is long relative to the period of the triangular modulating signal, the deviations in the difference frequency occurring at the turn around points of the modulating signal can be averaged out.

The circuit shown in Figure 7 was constructed and tested. While the theoretical concepts were valid, the circuit could not be made to perform within specifications. Even if it had worked as designed the performance would not have been acceptable. The filters operate with a constant Q, regardless of center frequency. Since Q,  $F_o$ , and BW are related by Eq. 2, changing  $F_o$  also changes BW linearly. The filters had been designed to have  $F_o$  range from 250 Hz to 5 KHz, with a BW of 20 Hz at  $F_o = 5$  KHz. Thus the Q of the filters would be 250, and at  $F_o = 250$  Hz the BW would be 1 Hz. Since the integration time of a filter is equal to the inverse of the filter bandwidth, the time required for the VCO to sweep from minimum range to maximum range would be

$$\text{Sweep Time} = \int_{250\text{Hz}}^{5\text{KHz}} (1 / \text{BW}) dF_o = \int_{250\text{Hz}}^{5\text{KHz}} (Q / F_o) dF_o \quad (3)$$

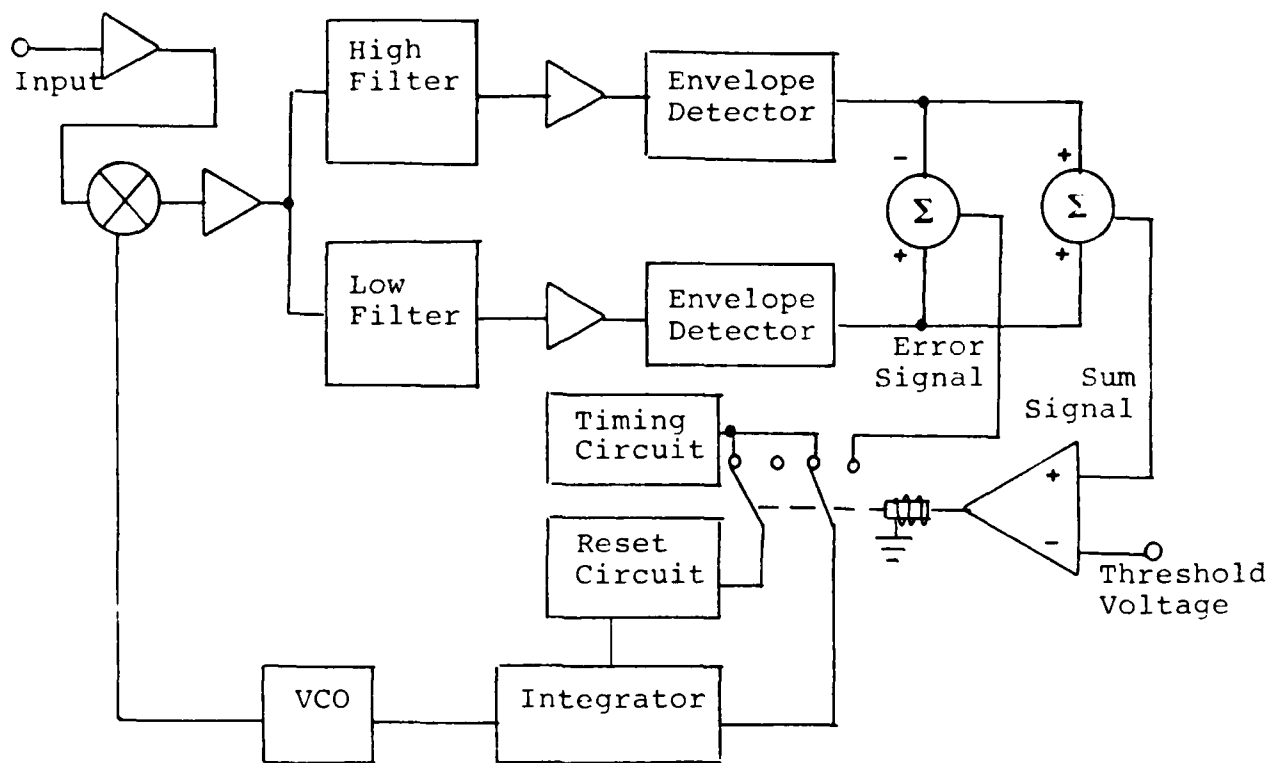


Figure 8. Final frequency tracking circuit.

If the target was at maximum range a full sweep would take over 12 minutes. This was deemed to be excessive, so the approach was discarded.

#### 4.3 Final Tracking Circuit Design

The original tracking circuit concept was to sweep the filter center frequencies past the target return frequency.

When this did not work, a slightly different approach was taken: sweep the target return frequency past the filter center frequencies. This was done by building the filters with fixed frequency responses. The peak response of each filter was set at a frequency higher than the maximum target return frequency, and the two filter center frequencies were offset from each other. Modulating the input signal with the output of an oscillator reproduces the input frequency spectrum at a higher frequency. Thus by sweeping the oscillator frequency, the modulated target return frequency can be made to sweep past the filters. A circuit designed to do this is shown in Figure 8.

Just as with the first tracking circuit, the key to the performance of this circuit was the filters. To obtain a higher  $Q$  than was achieved with the switched capacitor filters it was decided to use crystal filters. Crystal filters take advantage of the resonant properties of quartz to produce bandpass filters with quality factors that can exceed 1,000,000 [5:419-429]. By using more than one crystal it is possible to build bandpass filters with bandwidths that are greater than what can be achieved using just a single crystal. The design chosen for this application utilized two crystals per filter in what is called a half-lattice design. This configuration is illustrated in Figure 9.

Unlike the switched capacitor filters, crystal filters do not suffer from a fixed  $F_o \times Q$  product. Since higher  $Q$ 's can

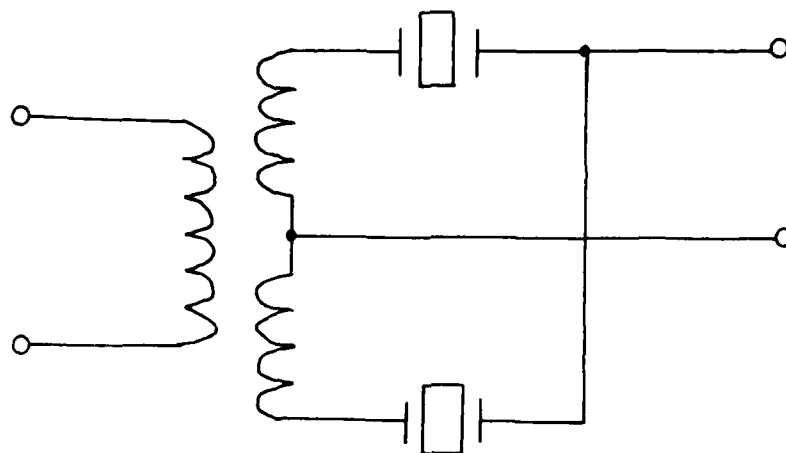


Figure 9. Half-lattice crystal filter.

be achieved and higher center frequencies used, the sweep rate of the oscillator can be increased. This produces more Hz per foot of target range, but not at the expense of filter bandwidth. Thus, the net result of using crystal filters is better target ranging accuracy.

The primary questions to be answered were what should the bandwidth be, and where should the center frequency be set? Since the circuit should no longer be limited by the performance of the filters other factors, such as doppler shift in the target return, can be considered in the design.

The amount of doppler shift created by a moving target is

$$f_{\text{dop}} = 2 V_r / \lambda \quad (4)$$

where  $V_r$  is the radial velocity of the target, and  $\lambda$  is the wavelength of the transmitted signal. With a maximum radial velocity of 4 knots, and using a wavelength of 3 centimeters (corresponding to a transmit frequency of 10 GHz), the maximum doppler frequency would be 137 Hz. As illustrated in Figure 4(a), a doppler shift will cause the difference frequency to vary by twice  $f_{\text{dop}}$ , or no more than 275 Hz. The filters need to be wider than this variation to insure that the target return signal stays in the filters. For these reasons it was decided to design the filters with bandwidths of 500 Hz. Choosing an oscillator sweep rate of 500 Hz per nanosecond means that two targets separated by one foot will have return frequencies spaced 1 KHz apart. Since this is greater than the 500 Hz bandwidth, one foot resolution is achievable.

The center frequency has to be set higher than the highest target return frequency -- but how high? Using a 500 Hz per nanosecond sweep rate gives a maximum range (500 feet) return frequency of 500 KHz, and a minimum range (25 feet) return of 25 KHz. If a 600 KHz filter center frequency were chosen, for example, the VCO would have to sweep from 100 KHz up to 575 KHz -- almost a 6:1 ratio. Since better VCO stability can be obtained at lower sweep ratios, it would be better to choose

a higher center frequency. For this reason it was decided to build the filters at a nominal center frequency of 5 MHz. Thus, the VCO would only have to sweep from 4.5 MHz to 4.975 MHz.

One more parameter remains to be selected in the filter design process: the amount of offset between the upper and lower filters. As shown in Figure 8, the filter outputs are used to form the sum and error signals. The ideal situation for a tracking circuit would be to have a sum volts vs. frequency response that is very high and narrow, and an error volts vs. frequency response that has a very steep slope as it crosses through zero volts. If the filters are not offset far enough (too much overlap) the sum pattern is good, but the error pattern has a low slope. Spreading the filters out too far raises the slope of the error signal, but it also puts a null in the center of the sum response. It was decided to give the filters a small amount of overlap, accepting a small null in the sum pattern in return for a steep error slope. If the filters are each 500 Hz wide and are centered at 4.9998 MHz and 5.0002 MHz, the filters will overlap by 100 Hz.



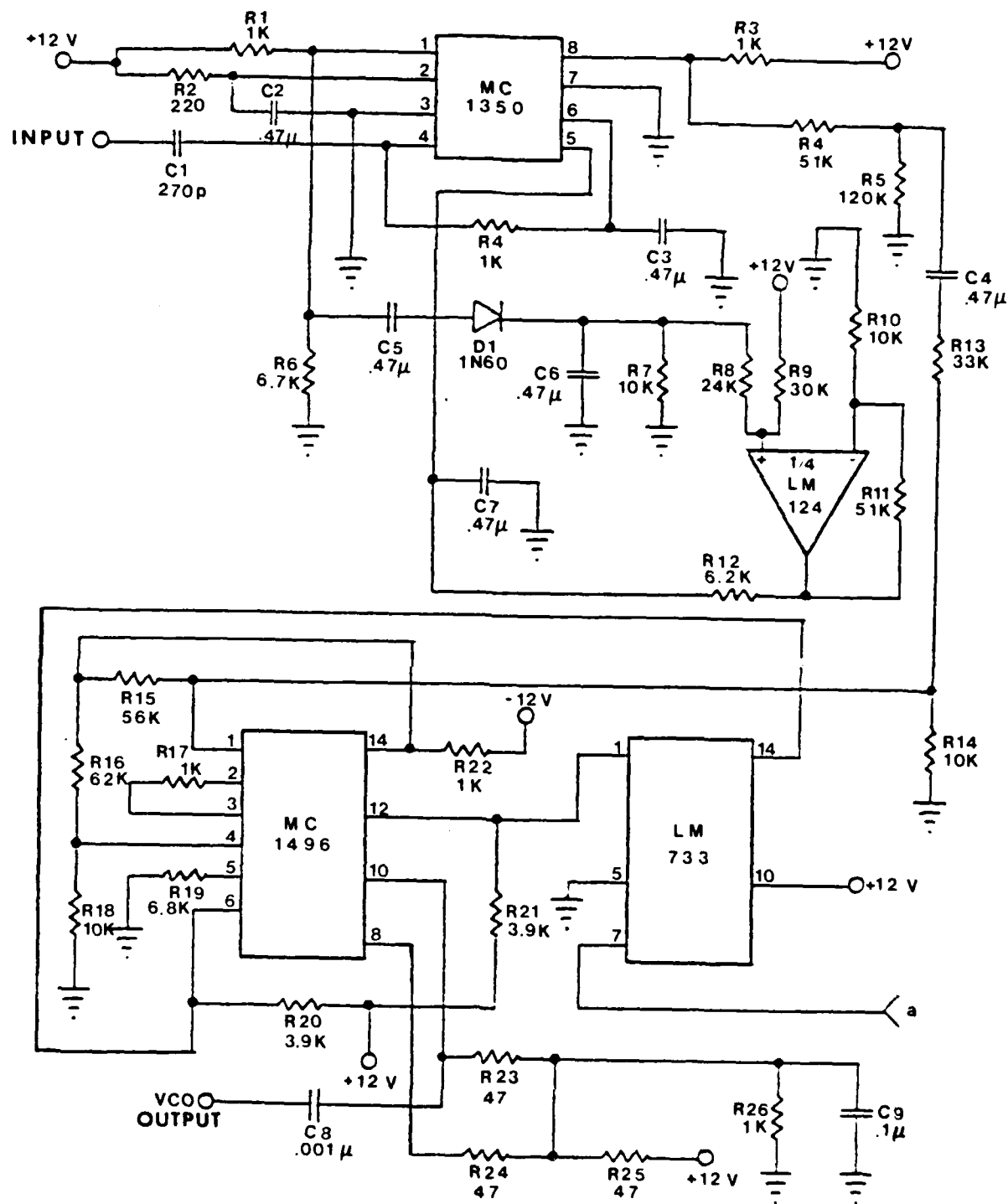


Figure 10. Tracking circuit schematic (Page 1 of 3).

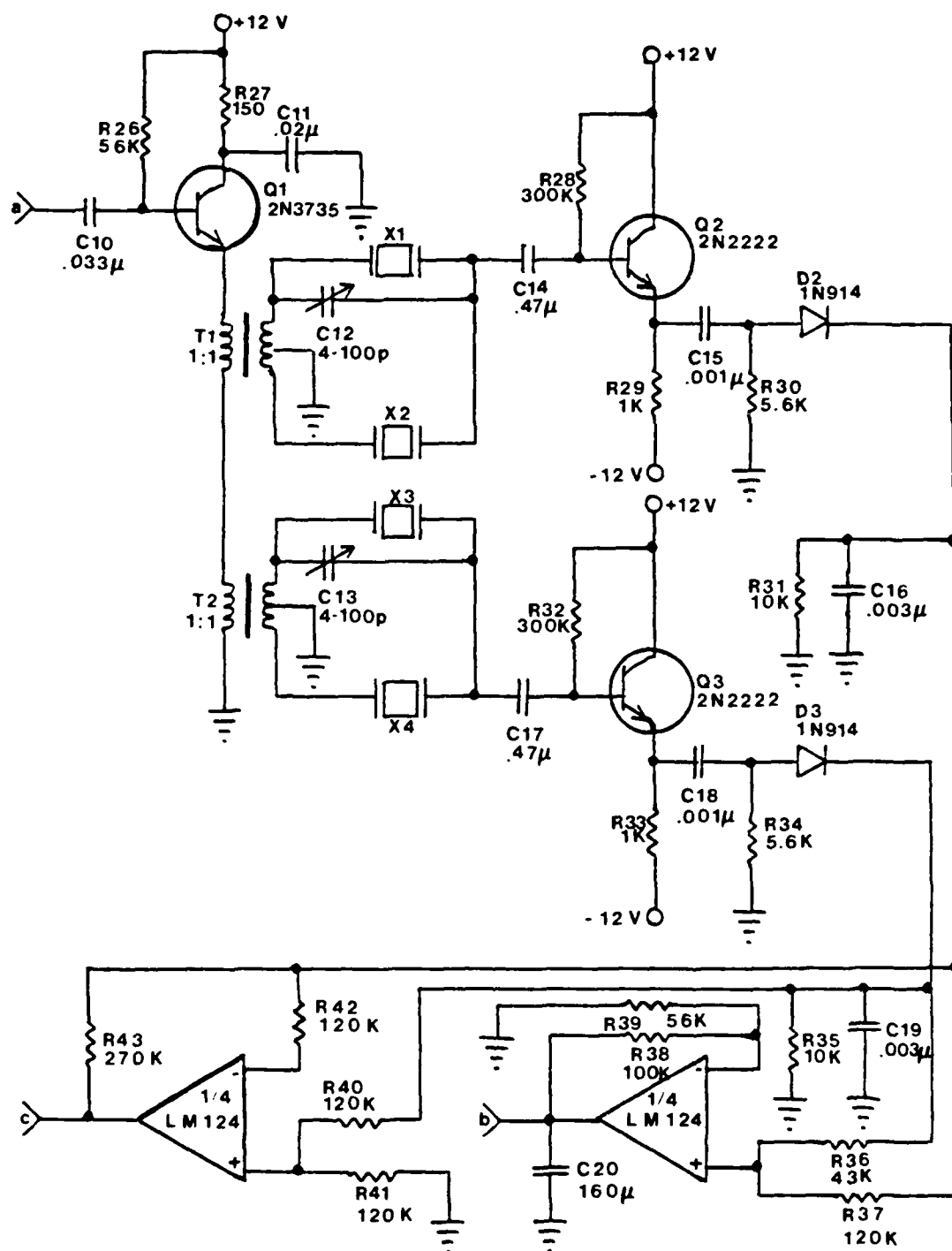


Figure 10. Tracking circuit schematic (Page 2 of 3).

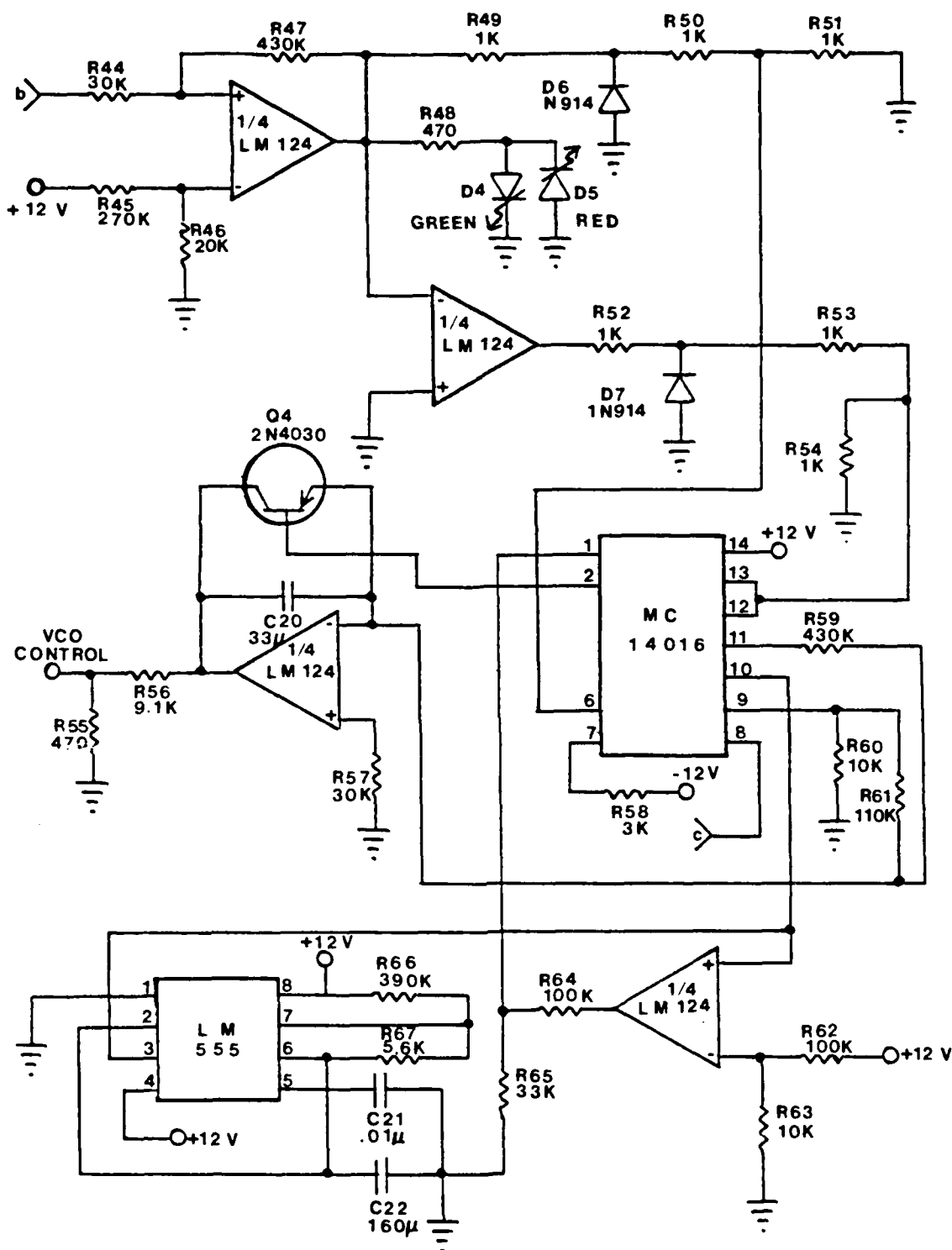


Figure 10. Tracking circuit schematic (Page 3 of 3).

A comparison of Figures 7 and 8 reveals that, excluding the filters, there is little difference between the two tracking circuit designs. Both circuits follow the filters with buffer stages before forming the sum and error signals. Both compare the sum signal to a threshold voltage to make a target present decision, and both apply either a timing signal or the error signal to an integrator. Each circuit uses the integrator output to control a VCO, but in the final tracking circuit the VCO output is applied to a modulator to shift the input frequency spectrum up to the frequency of the filters.

Figure 10 is a schematic diagram of the final tracking circuit. While at first glance the diagram appears very complex, it is not difficult to identify in the schematic each of the functional blocks shown in Figure 8. Input amplification is provided by a Motorola MC 1350 Monolithic Intermediate Frequency (IF) Amplifier. The output of the amplifier was kept constant by feeding one of the differential outputs back to the automatic gain control (AGC) input of the 1350. This enabled the amplifier output to remain constant while the input varied by as much as 50 dB. The function of the mixer (shown in Figure 8) was performed by a Motorola MC 1496 Balanced Modulator - Demodulator, which was adjusted to produce a suppressed carrier output. This output was passed to a National Semiconductor LM 733 Differential Video Amplifier whose purpose was to provide

input buffering for the crystal lattice filters.

The filters proved to be very difficult to build, because stray capacitance effects and changing loads cause the filter center frequencies and bandwidths to change. To lessen these problems both the high and low filters were followed by a buffer stage. Transistors Q2 and Q3 were each configured as emitter followers in an attempt to isolate the filters from the rest of the circuit.

All of the operational amplifier functions realized in the tracking circuit were constructed using National Semiconductor LM 124 Quad Op-Amps. These devices were used because they required no bias or frequency compensation adjustments and because, by getting four op-amps in a 14 pin package, the board that the tracking circuit was constructed on could be kept less crowded.

The output of the sum channel op-amp was connected to another op-amp which was used to make a target present/no target decision. This op-amp was configured as a comparator and, by using positive feedback, hysteresis was obtained in the decision process. When the tracking circuit was in a no target state a target present decision was only made when the sum voltage exceeded 1.5 volts, while the signal had to fall below .5 volts for the circuit to change from a target present to a no target state. Two light emitting diodes (LEDs) were connected to the output of the comparator to give

a visual indication of whether a target was present or not.

The comparator output was also connected to a Motorola MC 14016 Quad Analog Switch. When the comparator output was high (target present) the switch passed the error signal through to the integrator. When the comparator output was low (no target) the timing circuitry was connected to the integrator, and the integrator reset circuitry was enabled.

Originally, a VCO was built directly onto the tracking circuit board. A 74LS624 VCO chip was connected to the output of the integrator, but this approach did not work out. The VCO output was not stable enough: when given a constant input to its control pin, the frequency of the output of the '624 would intermittently jump by as much as 50 KHz. Many different chips were tried, but all behaved the same. In order to get a VCO that was stable enough it was necessary to connect the tracking circuit to an external VCO.

The circuit was constructed on a 4.25 by 6.25 inch circuit board. The board was plated on both sides, and it had holes pre-drilled in it for 2 dozen 16-pin dual inline packages (DIPs). Since one edge of the board was compatible with a 78 pin edge-card connector, this is how DC power was brought onto the board. All of the circuit components were mounted in wire wrap sockets, and connections were made by wire wrapping.

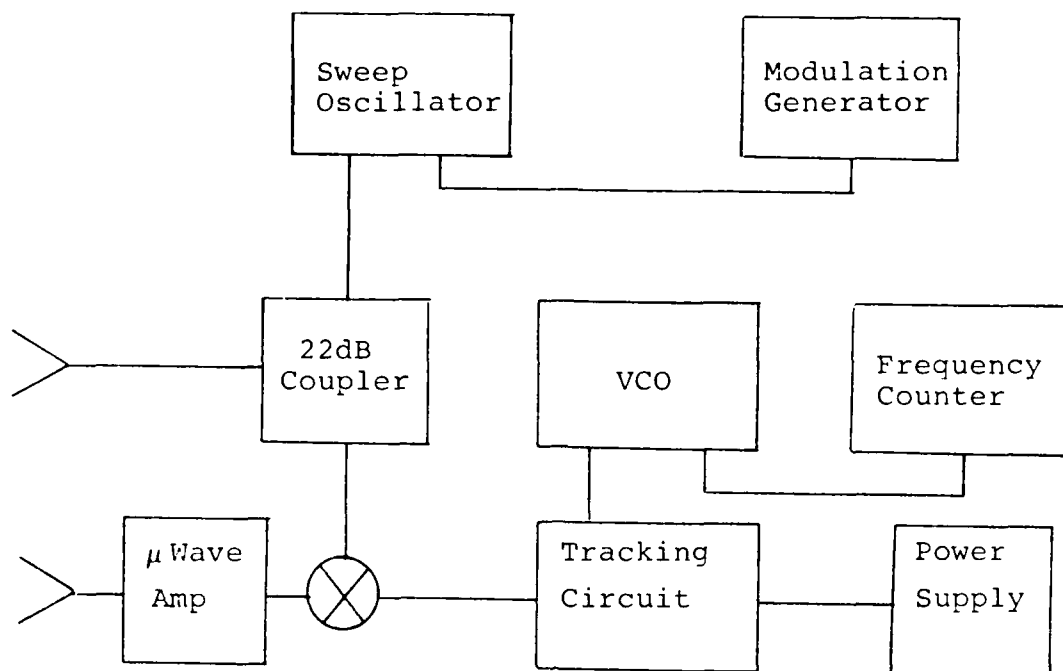


Figure 11. Ranging system components.

#### 4.4 Complete Ranging System Design

While the tracking circuit was designed from scratch, the rest of the ranging system was designed using laboratory test equipment. The advantages of using existing test equipment were that the system was completed faster, it was cheaper (the equipment was available and did not have to be purchased), and the design was simplified. The disadvantages

to this approach were that the system performance was constrained by the capabilities of the test equipment, the overall system was very bulky, and the amount of power consumed was probably higher than if the entire system had been constructed from the ground up. The layout of the ranging system is shown in Figure 11.

All of the equipment used in the ranging system (except for the tracking circuit) was commercially available laboratory test equipment. The RF signal was generated by a Hewlett-Packard (HP) 8350B Sweep Oscillator. This device is capable of generating signals over a wide band, depending on the range of the RF plug-in unit utilized. An HP 83545A RF Plug-In unit, covering the frequency band from 5.9 GHz to 12.4 GHz, was installed in the oscillator. The triangular modulating signal was generated by an HP 3312A Function Generator, and was applied to the external sweep input of the sweep oscillator. The RF output of the sweep oscillator was connected to an HP 11691 Directional Coupler. This device accepts RF energy as an input (from 2 GHz to 18 GHz) and generates two outputs: a direct output whose power level is essentially the same as the input signal's, and a coupled output whose power level is 22 dB below the input. The direct output of the coupler was connected to the transmit antenna, while the coupled output served as a local oscillator (LO) signal, and was fed to the microwave mixer.

Finding suitable antennas for the system was a distinct



problem. The antennas used in the system consisted of an 18 inch parabolic dish and a 9.5 by 5.5 inch horn. The dish was used for transmitting, while the horn was used as the receive antenna. The gain and beamwidth of the dish antenna were unknown. In fact, the entire antenna pattern was suspect because the dish had been dropped and the feed displaced. The feed was replaced in what looked like the original position but, since pattern measurement facilities were unavailable, the final antenna pattern was unknown. The horn antenna was an Emco Double Ridged Guide antenna, model 3105. This model is a linearly polarized, broadband antenna with an effective bandwidth from 1.0 GHz to 12.4 GHz. Data was available which indicated that, for the frequencies of interest, the horn had a gain of 13 dB.

The signal coming from the receive horn was fed to an HP 495A Microwave Amplifier. This device uses a travelling wave tube (TWT) to provide 30 dB of gain, and is effective from 7.0 GHz to 12.4 GHz. To get from the receive antenna to the mixer the signal had to pass through a six foot long section of RG-142 coaxial cable. The loss through the cable was measured and was found to be 6 dB. The HP 495A was used as an RF pre-amplifier in order to boost the signal before it suffered from the high cable loss.

The mixing was accomplished by injecting the LO signal and the received signal into a waveguide Magic-Tee. The received signal was applied to the difference arm of the Tee, while

the LO signal was applied to the sum arm. This arrangement was used because the sum arm of the Tee contained a vane attenuator, which allowed the LO signal power to be varied. The remaining two arms of the Tee each had 1N23 microwave diodes installed. The mixing of the LO and received signals was produced by the non-linear response of the diodes. The mixer output was taken from one diode, while impedance mismatch reflections were reduced by connecting the other diode to a 50 ohm load.

The output of the mixer was connected to the input of the tracking circuit. The power for the tracking circuit was generated by an HP 6236B DC Power Supply. The VCO control voltage and VCO output ports on the tracking circuit were connected to a Wavetek Model 186 Phase-Lock Generator, which served as the external VCO. The output of the VCO was also connected to an HP 5385A Frequency Counter. The counter was operated with a one second gating period, which allowed most of the noise induced fluctuations in the VCO output frequency to be averaged out. The frequency indicated on the counter served as the output of the ranging system.

## Chapter 5

### TEST RESULTS

Testing of the system was necessary to determine if the goals of the project (as listed in Chapter 2) were accomplished. This chapter looks at the tests that were done on the tracking circuit, and then examines the procedures used and results obtained from tests run on the entire ranging system.

#### 5.1 Tracking Circuit Tests

As explained earlier, the tracking circuit was the key component in the ranging system. Unlike many of the other system components whose settings can be altered by front panel adjustments, the performance of the tracking circuit cannot be changed easily. For this reason it was necessary to first determine the operating characteristics of the tracking circuit before integrating it with the rest of the ranging system.

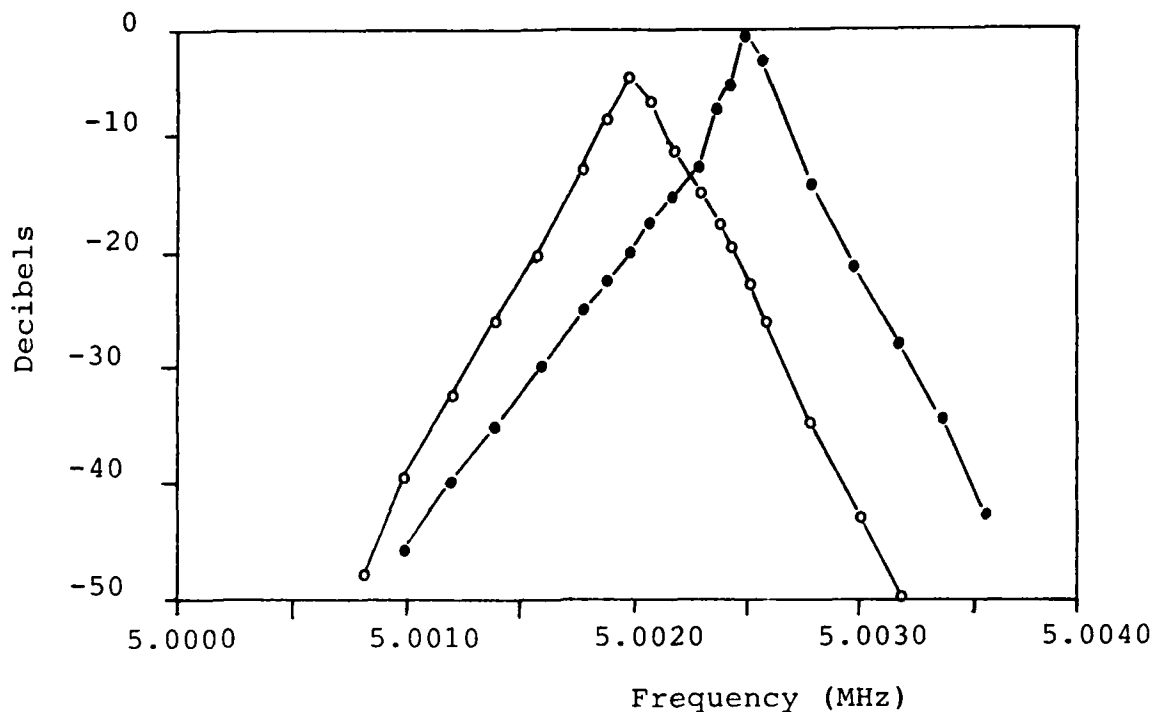


Figure 12. Upper and lower filter frequency response.

The first test performed on the tracking circuit was a measurement of the frequency response of the filters. The test was performed by injecting a sinusoid into the circuit before the filter input buffer amplifier (prior to C10 of Figure 10), and measuring the DC voltage levels coming out of the two envelope detectors (before R36 and R37). The frequency response of each filter is plotted in Figure 12. The vertical scale on this plot is in dB, relative to the highest voltage out of either filter. From the curves it can be seen that the 3 dB bandwidth of the high filter is 130 Hz, the bandwidth of the lower filter is 190 Hz, and the center

frequencies of the two filters are separated by 520 Hz.

While the separation of the filter center frequencies obtained here is reasonably close to what was originally desired (400 Hz), the bandwidth of each filter is much narrower than the 500 Hz that the design called for. A great deal of time and effort was devoted to trying to get the filter specifications closer to the design goals. This task was very difficult because any changes to the filter design affected the bandwidth, center frequency and gain of the filter simultaneously. The problem that an operational system would have by using filters that were too narrow is that the maximum relative target velocity that the system could track would decrease. As shown in Figure 4(a), a doppler frequency causes the difference frequency to alternate up and down. A target doppler frequency that was too large would cause the frequency being tracked to jump out of the filter and lock-on would be lost. Since no tests were to be conducted of this system against moving targets, it was decided to leave the filters as they were and proceed.

The next tests performed were measurements of the sum volts vs. frequency and the difference volts vs. frequency. In each test the input was again injected prior to C10. The sum volts were measured at the output of the sum amplifier (at point b of Figure 10), while the difference volts were measured at the output of the difference amplifier (point c of Figure 10). The two curves are plotted vs. frequency in

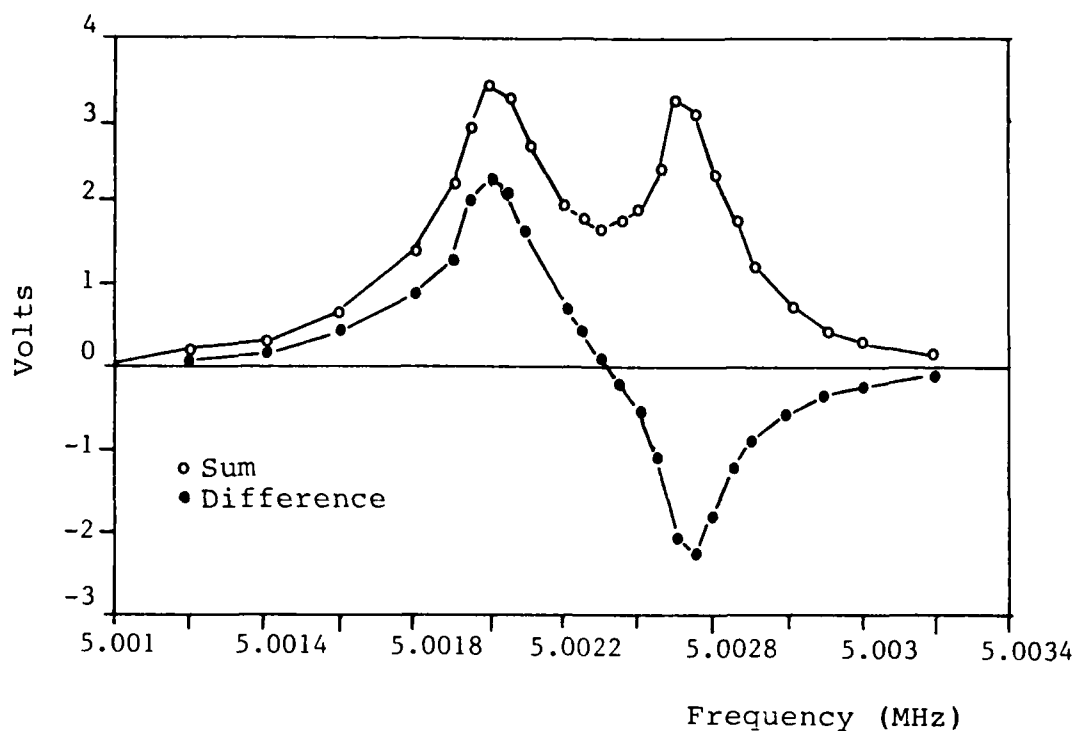


Figure 13. Sum and difference volts vs. frequency.

Figure 13. By plotting them in the same figure it is easy to see that the zero crossing of the difference curve occurs at approximately the same frequency as the null in the sum curve. The depth of the null in the sum pattern determined the setting of the target threshold. The threshold had to be set high enough so that noise would not cause a false alarm, but low enough so that a target centered in the filters would not cause the comparator to toggle to a no target state.

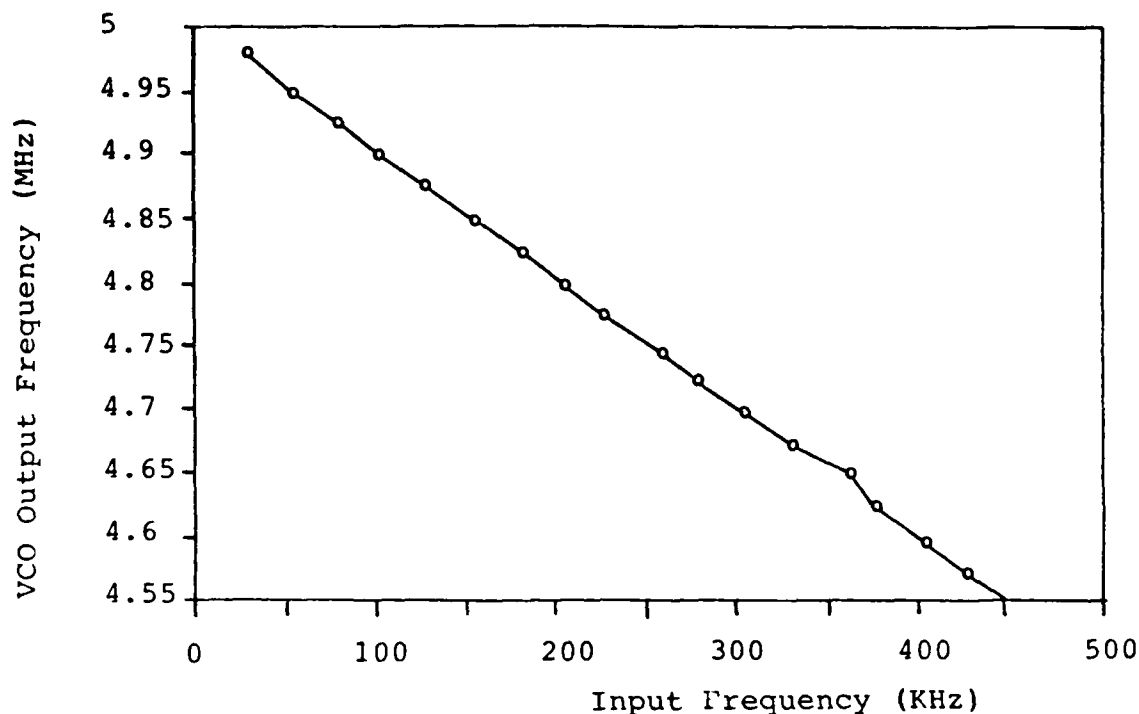


Figure 14. VCO output frequency vs. input frequency.

Prior to integrating the tracking circuit with the rest of the ranging system the tracking circuit and external VCO were tested together. The VCO control port on the tracking circuit was connected to the VCO, and the output of the VCO was connected to the VCO output port on the tracking circuit. A sinusoid was fed to the tracking circuit input connector and the VCO output was hooked up to a frequency counter. Figure 14 shows the resulting relationship between the input frequency and the VCO output frequency. It should not be surprising that this curve is so linear: if the tracking circuit is locked on and stable, the sum of the

input frequency and the VCO output frequency must equal the frequency where the difference curve passes through zero volts.

## 5.2 Complete Ranging System Tests

The purpose of testing the entire ranging system was to verify that the goals outlined in Chapter 2 had been accomplished. Specifically, these goals were to demonstrate the ability to measure target range from 25 to 400 feet, and to measure the range with an accuracy of  $\pm 1$  foot. Also, to ensure that the system would operate effectively against complex targets (aircraft), testing was done to determine if two targets separated by one foot could be resolved.

The first problem encountered when trying to test the complete ranging system was locating a suitable place to conduct the tests. The site selected needed to be a clear area, free of significant radar reflectors for a radius of at least 500 feet. It needed to be away from populated areas to prevent any possibility of exposing people to RF radiation. And it needed to have a source of 60 Hz electricity with enough power to be able to run all of the test equipment. A site was located that met all of these requirements, but with one problem: the grass in the area was about one foot high.



The grass would present a relatively high clutter return to the radar. The test range was measured and stakes were driven into the ground at regular intervals to serve as range markers. The ranging system and support equipment (oscilloscope, spectrum analyzer, RF power meter) were housed inside a panel truck, which was parked at the edge of the test range. The rear doors of the truck were opened and the transmit and receive antennas were placed in the doorway.

The target used for the first test was a standard triangular corner reflector mounted on a 3 foot long pole. The radar cross section of a triangular trihedral reflector can be calculated using

$$\sigma = 4\pi (0.289 L^2)^2 / \lambda^2 \quad (5)$$

where  $L$  is the length of the perpendicular sides. Since this target was 13.5 inches long on each side this indicates that (using a wavelength of 3 centimeters) the target had a maximum radar cross section of 16.1 square meters. Alignment of the axis of the corner reflector was done visually: since triangular corner reflectors have a wide reflective pattern [6:27-15] it was felt that any loss of cross section due to misalignment of the target would be negligible.

Upon applying power to the system the first step was to verify that the system was operating and attempt to optimize

its performance. The first problem encountered was with the sweep oscillator. It was originally set up to sweep over a bandwidth of 250 MHz at a modulation frequency of 1 KHz. Examination of the RF output on the spectrum analyzer revealed that it was not capable of being swept at that frequency. Lowering the sweep frequency to 500 Hz produced an RF output that was flat across the 250 MHz band, but this also lowered the sweep rate from 500 Hz/nanosecond to 250 Hz/nanosecond. Since this would divide the accuracy of the system by a factor of two the bandwidth was doubled, up to 500 MHz.

When the system was operated at these settings it would lock on only for short periods of time (typically from 20 to 30 seconds) before breaking lock and starting a new search for the target. When it was locked on the VCO frequency was not very stable: it would jump between two different frequencies intermittently. The reason for this was found to be the 500 Hz modulation frequency. The difference frequency was not constant, but was actually being modulated at a 500 Hz rate. This means that the difference frequency spectrum consisted of discrete spectral lines separated by 500 Hz. Since the center frequencies of the upper and lower filters were separated by 520 Hz the tracking circuit was randomly trying to track first one line, and then another.

The solution to this problem was to lower the modulating frequency again, this time to 100 Hz. To maintain a 500

Hz/nanosecond sweep rate the RF bandwidth was set at 2.5 GHz (sweeping from 8 GHz to 10.5 GHz). A check of the output of the sweep generator with a spectrum analyzer proved that it would meet this requirement, and yet the system still would not lock on solidly. A comparison of the difference output of the mixer with the triangular modulating signal revealed that the amplitude of the difference signal fell drastically when the RF output was at the higher frequencies. Some part of the system between the sweep generator and the mixer (either the coaxial cables, the microwave amplifier, or either of the two antennas) could not support frequencies that high.

The only way that the system could be made to work was to lower the highest frequency that the system swept to. Since parts of the system had a fixed minimum frequency that they would operate at, the only alternative was to reduce the RF bandwidth of the system. It had already been determined that the modulating frequency could not be increased so decreasing the bandwidth resulted in lowering the sweep rate of the system. The final figures that were settled on were to sweep from 7.75 GHz to 8.75 GHz. Since this was done at 100 Hz the sweep rate was 200 Hz/nanosecond. The system was designed to produce one foot accuracy at a sweep rate of 500 Hz/nanosecond, so lowering the sweep rate to 200 Hz/nanosecond will degrade the accuracy by a factor of 500/200. The end result is a system accurate to 2.5 feet.

Table I. Range accuracy test results.

Range (feet)	$F_{\text{measured}}$ (Hz)	$F_{\text{calculated}}$ (Hz)	$\Delta F$ ( $F_m - F_{\text{cal}}$ )	$(\Delta F)^2$ (Hz <sup>2</sup> )
25	4992404	4992902	-498	248427
50	4981810	4982575	-765	584996
75	4972422	4972247	175	30529
100	4962074	4961920	154	23808
125	4953912	4951592	2320	5381820
150	4940687	4941265	-578	333564
175	4930526	4930937	-411	168900
200	4920173	4920609	-436	190445
225	4910235	4910282	-47	2193
250	4901268	4899954	1314	1725939
275	4888388	4889627	-1239	1534316

The first test that was run on the system was a range accuracy test. The procedure used was to place the target at a known range, record the frequency of the VCO output, and then move the target farther out in range and repeat the test. This was continued until the target was too far out for the system to achieve lock on. The measured data that was obtained is listed in Table I.

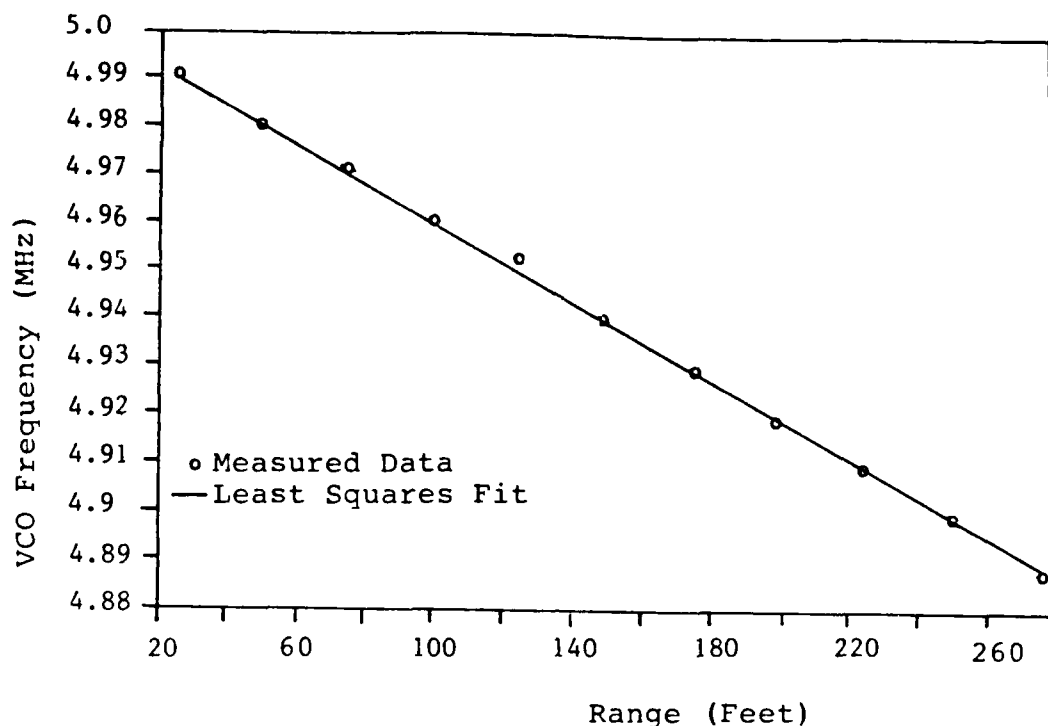


Figure 15. System range vs. frequency response.

The measured data was run through a linear regression software routine to generate the equation for a least squares straight line. This equation was found to be

$$F_{cal} = (-413.033 \text{ Hz/foot}) \times \text{Range} + 5,003,230 \text{ Hz} \quad (6)$$

where  $F_{cal}$  is the value of the frequency calculated by the equation. This equation and the measured data points are plotted in Figure 15. The measured and calculated values of frequency were compared in an attempt to find the mean square error of the system. The mean value of the squared difference between these two numbers was found to be

$$\text{Mean}[(\Delta F)^2] = 929540 \text{ Hz}^2 \quad (7)$$

The square root of this number is the mean square error in frequency -- 964 Hz. Dividing this number by the 413.033 Hz/foot sweep rate of the system the error becomes 2.33 feet.

While the maximum range specified for this system was 400 feet and the goal of the design effort had been 500 feet, lock-on could only be achieved out to 275 feet. The power level coming out of the sweep oscillator was 26 dBm, and after suffering a 6 dB loss in the coaxial cable between the coupler and the transmit antenna only 20 dBm was transmitted. In an effort to increase this amount another RF power amplifier was obtained. This device was placed directly before the transmit antenna and it boosted the transmitted power level to 43 dBm. Even with 23 dB more power being transmitted the maximum range remained 275 feet. The maximum range was not being limited by signal to noise limitations, but by the received signal to clutter level. If the grass had been shorter or the target could have been elevated higher the clutter return power would have decreased and the maximum range of the system would have increased.

The last test performed was an attempt to measure the range resolution of the system. Two triangular corner reflectors

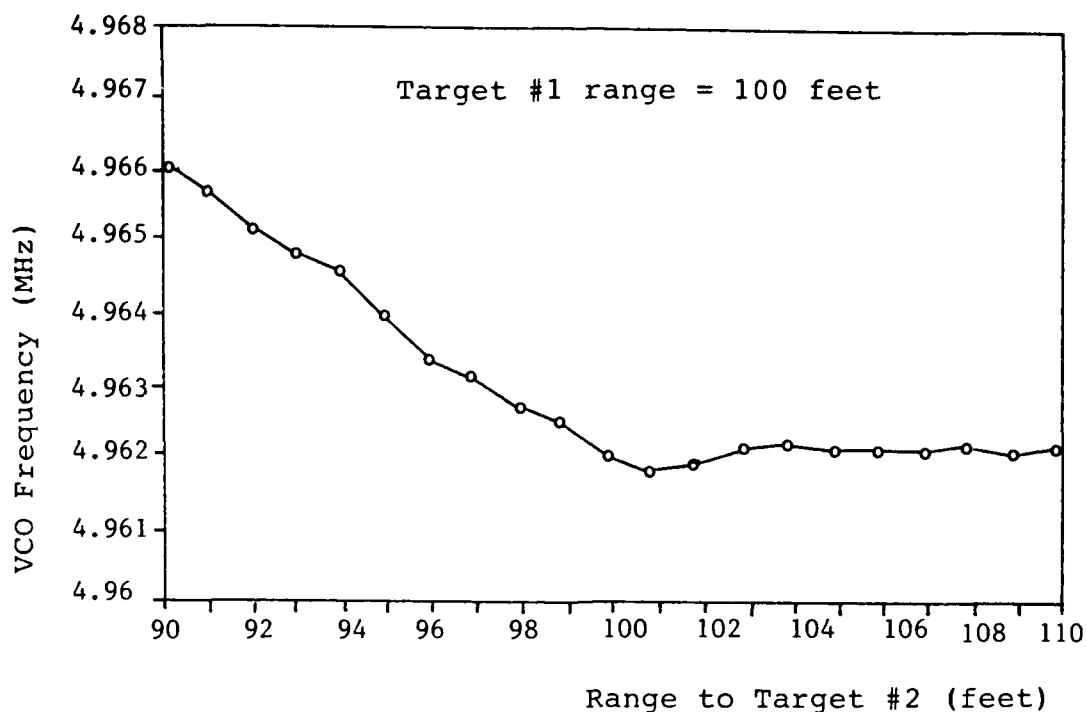


Figure 16. Range resolution test results.

of equal size (12 inches along the perpendicular sides) were manufactured. Target #1 was placed at a range of 100 feet and its axis was aligned with the transmit and receive antennas. Target #2 was placed ten feet farther out and the VCO frequency was recorded. Target #2 was then moved in one foot and the frequency was recorded again. This procedure was repeated until target #2 was at a range of 90 feet (10 feet closer in than target #1). The results of the test are plotted in Figure 16.

Examination of Figure 16 reveals that as target #2 begins to move in from 110 feet the VCO frequency is independent of the farthest target. This continues until the separation between the two targets decreases to about two feet, where the system begins to track the centroid of the two targets. As the range to target #2 becomes less than 98 feet the system tracks only target #2, and the VCO frequency increases as the range to that target decreases. While it might be difficult to come up with an exact number for the range resolution of the system based on this data it would not be unreasonable to approximate it as two feet.



## Chapter 6

### CONCLUSIONS AND RECOMMENDATIONS

This chapter will examine the results that have been obtained and compare them with the goals listed in Chapter 2. Also, some possibilities for future study and testing in this area will be recommended.

#### 6.1 Conclusions

One of the specified performance measures of this ranging system was the minimum and maximum range at which it could lock on to a target. A minimum range of 25 feet had been specified and, indeed, the system worked well at that range. While a maximum range of 400 feet had been desired only 275 feet was attained. What would be required to extend the maximum range to 400 feet? By showing that adding more transmitter power was not the answer it became clear that this system (as tested) was not limited by signal to noise ratio, but by signal to clutter ratio. Certainly the maximum range

could have been extended by using a larger target. This is not practical because the system must be able to work against complex targets composed of many radar scatterers, many of which are not large. It also could have been extended by reducing the clutter power either of two ways: by raising the target above the clutter, or by increasing the range to the clutter. Raising the target would increase the maximum range of the system when operated on the ground. If the system is operated in an airborne environment like that described in Chapter 2 the range to the clutter would increase by many orders of magnitude and the maximum range would certainly extend well beyond 400 feet.

The other key performance measure of this system was the range accuracy that it could achieve. The system was designed to have  $\pm 1$  foot accuracy but the mean square error of the system was no better than 2.33 feet. The range accuracy of an FM-CW system is directly related to the sweep rate used. A rate of 1 KHz per nanosecond was desired for the system but the available test equipment could only support a rate of 400 Hz per nanosecond. Since the 2.33 feet that was achieved is slightly better than the 2.5 feet accuracy that was predicted using this rate there is no doubt that, given equipment that will support a rate of 1 KHz per nanosecond,  $\pm 1$  foot accuracy is possible.

## 6.2 Recommendations

This effort proved the feasibility of achieving high accuracy at short ranges. Future efforts that use a similar approach should consider the following hardware improvements:

1. The crystal filters need to be improved. While the frequency that the two filters are centered at is not critical their bandwidths and offset from each other is. Compromises in this area will adversely effect the performance of the ranging system.
2. The maximum sweep rate possible should be used. One option to consider is to develop the frequency sweep at a lower frequency band and then modulate it up to the final transmit frequency band.
3. Find a stable VCO chip that can be put on the same circuit board as the rest of the tracking circuit. A stable VCO is crucial for insuring that the system maintains lock-on. Putting the VCO on the board with the rest of the circuit decreases the size, weight, and power consumption of the system.

The system that was constructed worked well against simple targets on the ground. The final test that needs to be run is a test of this system, or a modified system, against an airborne target.

## BIBLIOGRAPHY

1. Schultz, James B. "Navstar GPS Offers Mid-Course Guidance Improvements to Cruise Missiles," Defense Electronics, 16: 66-70 (May 1984).
2. Bachman, Christian G. Laser Radar Systems and Techniques. Dedham, MA: Artech House, Inc., 1979.
3. Saunders, William K. "CW and FM Radars," Radar Handbook, edited by Merrill I. Skolnik. New York: McGraw-Hill Book Company, 1970.
4. CMOS Databook, National Semiconductor Corporation, Santa Clara, CA, 4-21 through 4-31, 1984.
5. Kosowsky, David I. "High Frequency Crystal Filter Design Techniques and Applications," Proceedings of the IRE, 46: 419-429 (February 1958).
6. Kell, R. E. and R. A. Ross. "Radar Cross Section of Targets," Radar Handbook, edited by Merrill I. Skolnik. New York: McGraw-Hill Book Company, 1970.

## VITA

Captain Kurt E. Thomsen was born in Toledo, Ohio, on 22 December 1953. He enlisted in the USAF in 1975 and was assigned to the 318th Fighter Interceptor Squadron, McChord AFB, Washington, as a Missile Systems Maintenance Specialist. After being accepted into the Airmans Education and Commissioning Program he enrolled at the University of Illinois in 1979. He was awarded the Bachelor of Science in Electrical Engineering degree in August 1980, and was a Distinguished Graduate of Officer Training School in November 1980. He was then assigned to the Aeronautical Systems Division, Wright-Patterson AFB, Ohio, where he served as a Radar Systems Engineer until entering the School of Engineering, Air Force Institute of Technology, in May 1983.

Permanent address: 4832 Amesbury Road  
Toledo, Ohio 43612

AD-A152195

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GE/ENG/84D-66			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION School of Engineering, Air Force Institute of Technology		6b. OFFICE SYMBOL (If applicable) AFIT/EN	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State and ZIP Code)			7b. ADDRESS (City, State and ZIP Code)		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State and ZIP Code)			10. SOURCE OF FUNDING NOS.		
11. TITLE (Include Security Classification) See Box 19			PROGRAM ELEMENT NO.		PROJECT NO.
			TASK NO.		WORK UNIT NO.
12. PERSONAL AUTHOR(S) Kurt E. Thomsen, B.S., Capt, USAF					
13a. TYPE OF REPORT MS Thesis		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Yr., Mo., Day) 1984 December	
15. PAGE COUNT 76					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB. GR.	Radar Tracking, Range Finding, Short Range		
17	09				
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Title: A SHORT RANGE, HIGH ACCURACY RADAR RANGING SYSTEM</p> <p>Thesis Chairman: Kenneth G. Castor, Major, USAF</p>					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT			21. ABSTRACT SECURITY CLASSIFICATION		
UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS <input type="checkbox"/>			UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Kenneth G. Castor, Major, USAF			22b. TELEPHONE NUMBER (Include Area Code) 513-255-3576		22c. OFFICE SYMBOL AFIT/ENG

This paper describes the design and test of a low power, highly accurate FM-CW radar ranging system. The objective of the design was to provide an inexpensive aircraft-to-aircraft ranging system with  $\pm 1$  foot accuracy at ranges up to 400 feet.

Particular detail is given to describing the design and test of the frequency tracking circuit. Quartz crystals were used to make the narrow bandpass filters necessary for good frequency resolution. The design of the rest of the system was kept simple by using standard electronic test equipment.

The system was tested for its range accuracy and range resolution capabilities. The results show that the system was limited by ground clutter and the performance of the test equipment available. However, given the right equipment in an airborne environment the accuracy desired for the system is possible.

ORIGINATOR - SUPPLIED KEY WORDS INCLUDE:



**END**

**FILMED**

**4-85**

**DTIC**